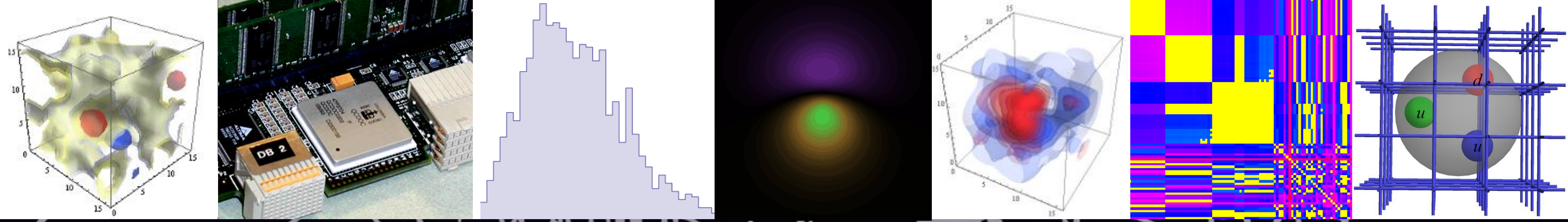
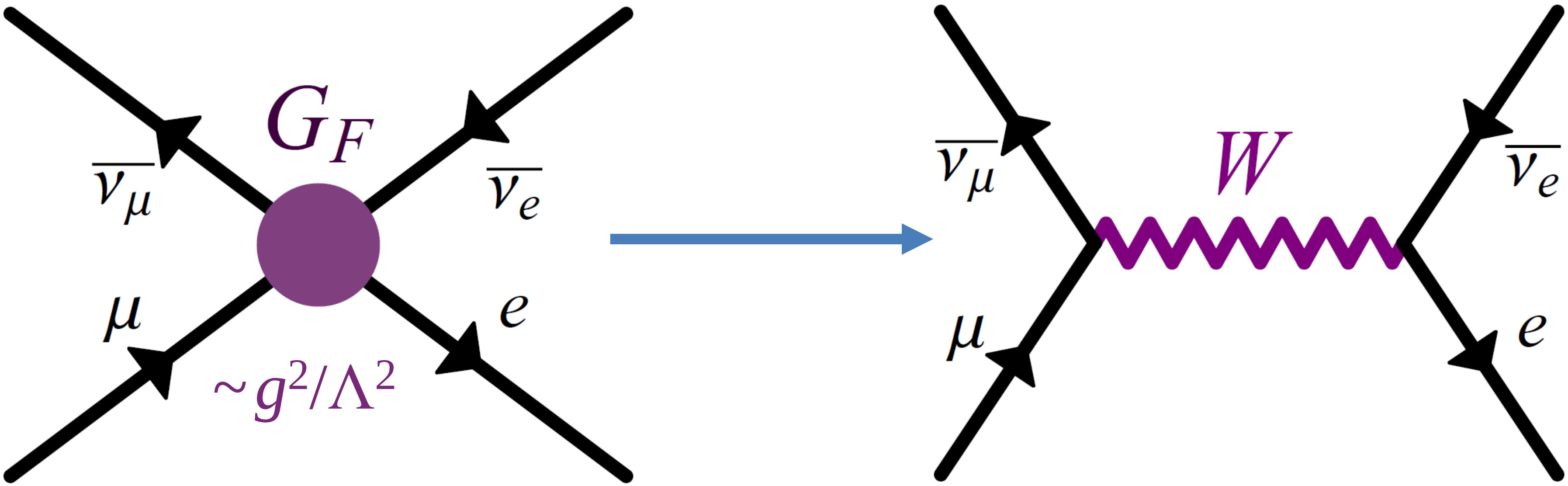


Probing TeV Physics through Lattice Neutron-Decay Matrix Elements

Saul D. Cohen (for PNDME Collaboration)
University of Washington

Fermi Theory of Beta Decay

- § Four-fermion interaction explained beta decay before electroweak theory was proposed
  - New operators in effective low-energy theories
- § Electroweak theory adds 3 vector bosons
  - *W* and *Z* bosons directly detected later at CERN

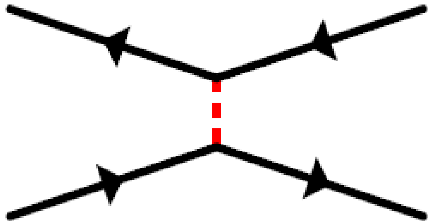


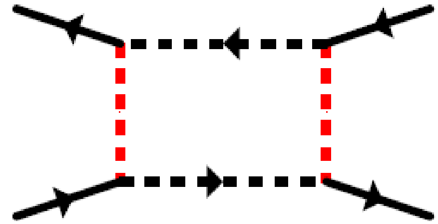
$$\Lambda \approx m_W \approx 80\text{ GeV}, m_Z \approx 90\text{ GeV}$$

What You See/How You Look

E

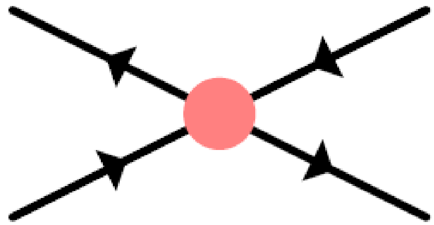
$\Lambda_{\mathrm{BSM}} \approx \mathrm{TeV}$





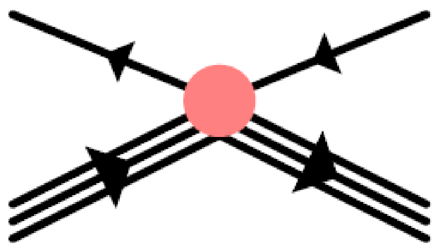
$$L_{\mathrm{SM}} + L_{\mathrm{BSM}}$$

$M_{W,Z}$



$$L_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\hat{O}_i$$

$\Lambda_{\mathrm{QCD}} \approx \mathrm{GeV}$



$$g_S = \langle n|\overline{u}d|p\rangle$$

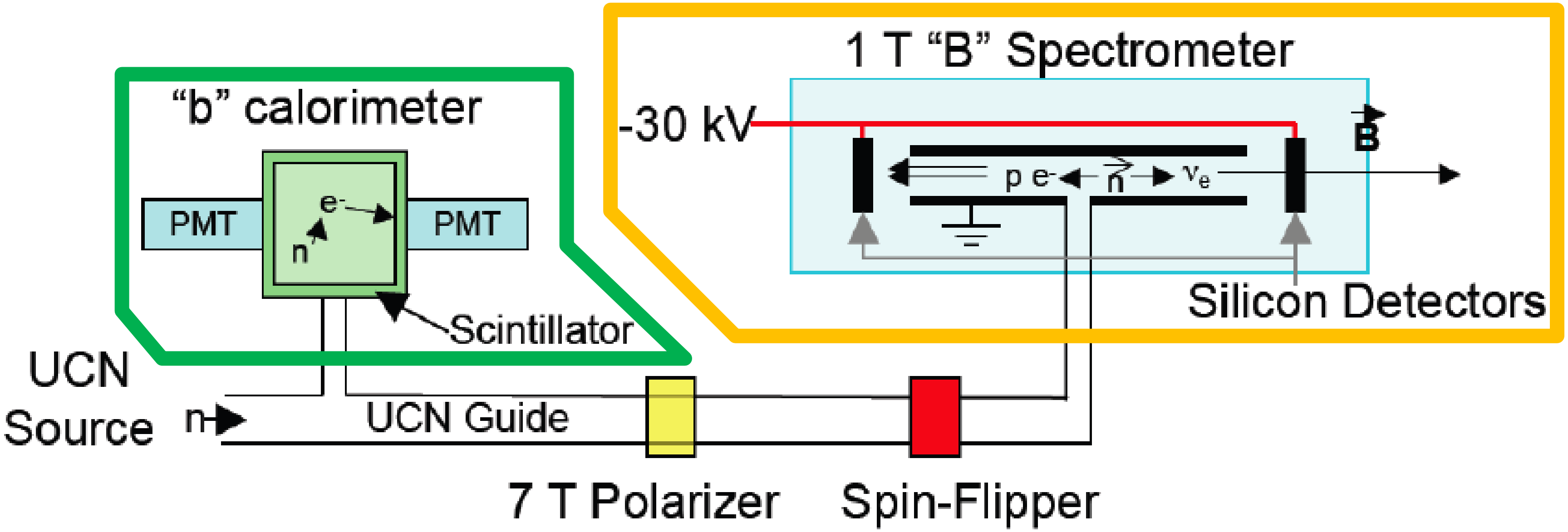
$$g_T = \langle n|\overline{u}\sigma_{\mu\nu}d|p\rangle$$

Neutron Beta Decay

§ Experiments measure the total neutron decay rate

$$d\Gamma \propto F(E_e)\left[1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + A\frac{\vec{\sigma}_n\cdot\vec{p}_e}{E_e} + \boxed{b\frac{m_e}{E_e}} + \left(B_0 + \boxed{B_1\frac{m_e}{E_e}}\right)\frac{\vec{\sigma}_n\cdot\vec{p}_\nu}{E_\nu} + \cdots\right]$$

- Within the Standard Model, a and A are $O(10^{-1})$, B_0 is $O(1)$, b and B_1 are $O(10^{-3})$



BSM Interactions

§ Theoretically, *b* and B_1 are related to new interactions: the scalar and tensor

$$H_{\text{eff}} = G_F \left(J_{V-A}^{\text{lept}} \times J_{V-A}^{\text{quark}} + \sum_i \varepsilon_i^{\text{BSM}} \hat{O}_i^{\text{lept}} \times \hat{O}_i^{\text{quark}} \right)$$

$$\hat{O}_S = \overline{u}d \times \overline{e}(1-\gamma_5)\nu_e \quad \rightarrow \quad g_S = \langle n|\overline{u}d|p\rangle$$

$$\hat{O}_T = \overline{u}\sigma_{\mu\nu}d \times \overline{e}\sigma^{\mu\nu}(1-\gamma_5)\nu_e \quad \rightarrow \quad g_T = \langle n|\overline{u}\sigma_{\mu\nu}d|p\rangle$$

- ε_S and ε_T are related to the masses of the new TeV-scale particles
- … but the unknown coupling constants $g_{S,T}$ are needed
- These are nonperturbative functions of the neutron structure, described by quantum chromodynamics (QCD)

Physics Program

§ Given precision $g_{S,T}$ and b, B_1, we can predict possible new particles

UCNs by 2013

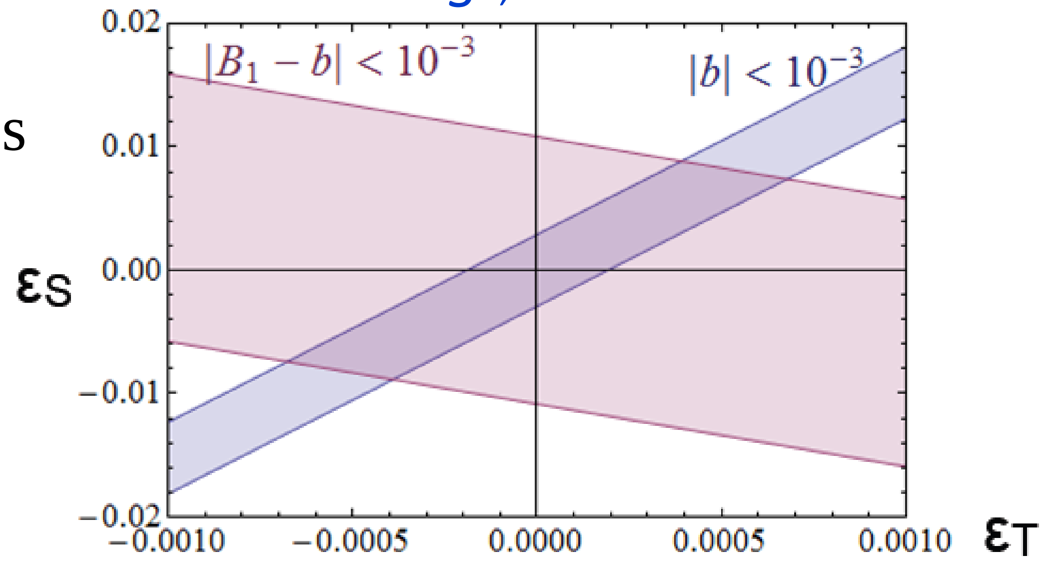
$$b = f_b\,(\varepsilon_{S,T}\,g_{S,T})$$
$$B_1 = f_B\,(\varepsilon_{S,T}\,g_{S,T})$$

Precision LQCD input ($m_\pi \approx 140$ MeV, $a \to 0$)

ε_S and ε_T

- Give the scale of particles mediating new forces

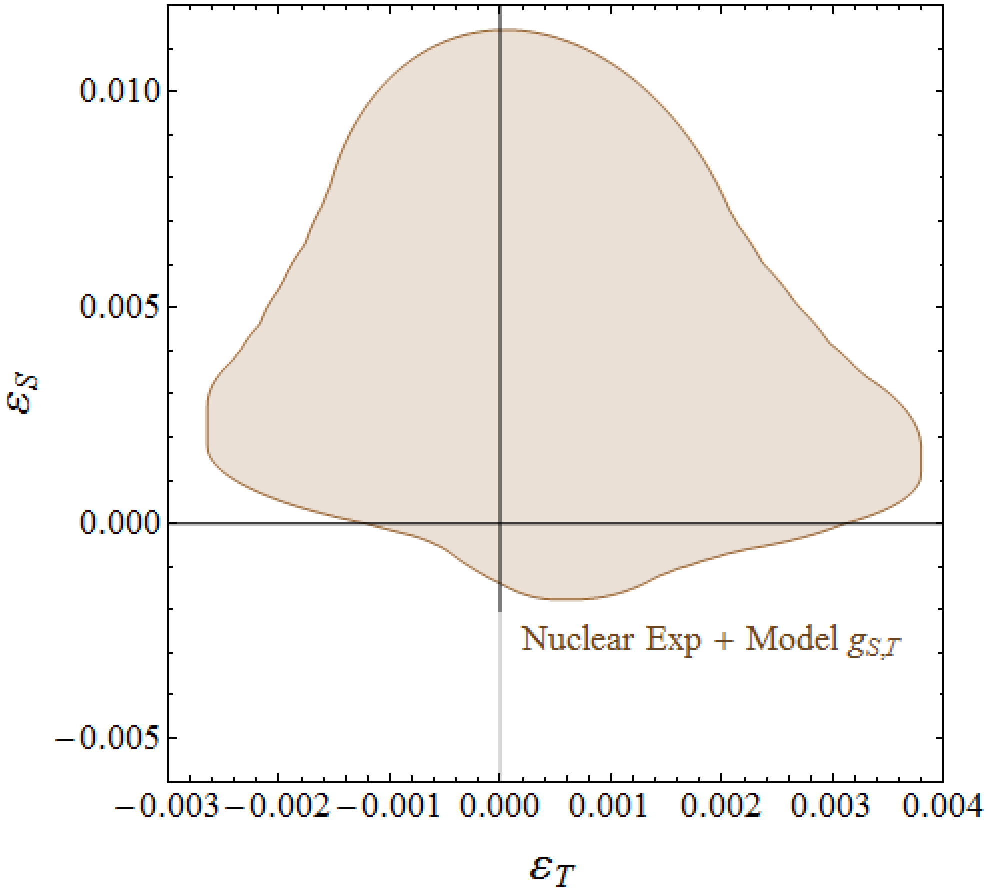
$g_{S,T} = 1$



Current Constraints

§ Given precision $g_{S,T}$ and O_{BSM}, predict new-physics scales

Nuclear Exp. $\rightarrow$ $\boxed{O_{BSM} = f_O(\varepsilon_{S,T}\, g_{S,T})}$ $\leftarrow$ Model input



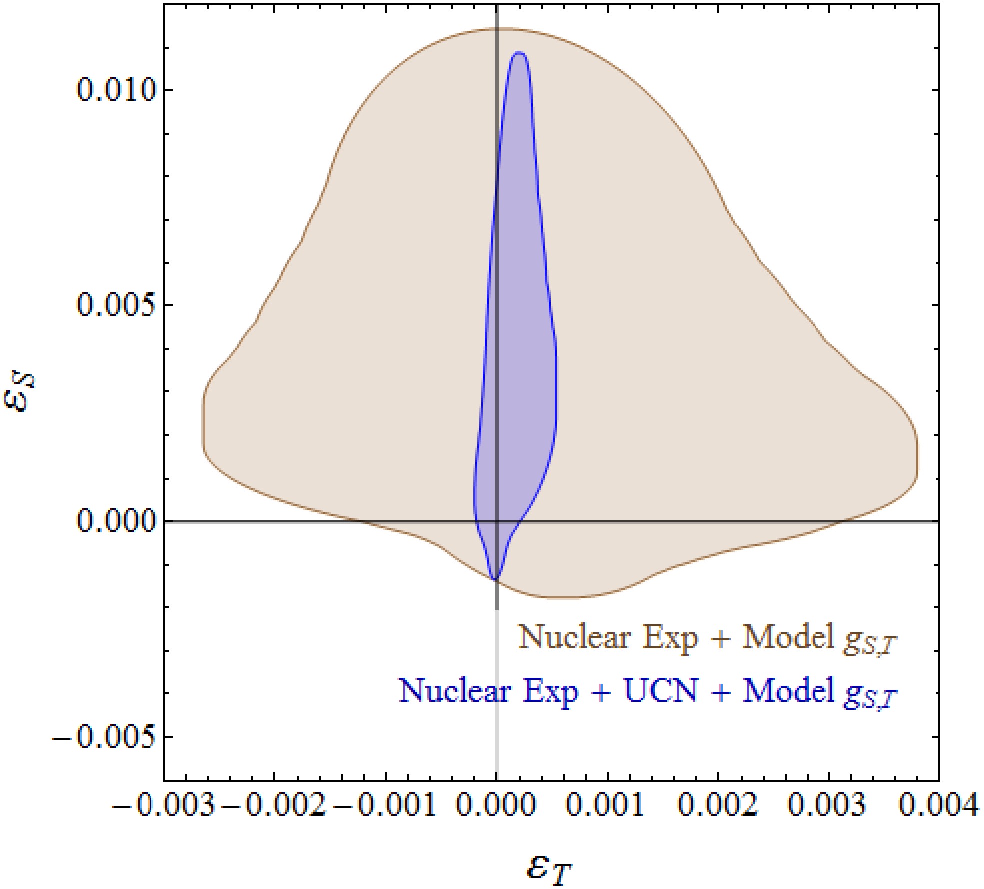
$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$

- Nuclear beta decays
  - $0^+ \longrightarrow 0^+$ transitions
  - β asym in Gamow-Teller ^{60}Co
  - polarization ratio between Fermi and GT in ^{114}In
  - positron polarization in polarized ^{107}In
  - β-ν correlation parameter a

Reach of UCN Experiments

§ Given precision $g_{S,T}$ and $O_{\rm BSM}$, predict new-physics scales

New UCN Exp. → $O_{\rm BSM} = f_O(\varepsilon_{S,T}\, g_{S,T})$ ← Model input



$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$

LANL UCN neutron decay exp't

$$d\Gamma \propto F(E_e)\left[1 + \boxed{b\frac{m_e}{E_e}} + \left(B_0 + \boxed{B_1\frac{m_e}{E_e}}\right)\frac{\vec{\sigma}_n\cdot\vec{p}_\nu}{E_\nu} + \cdots\right]$$

Expect by 2013:

$$|B_1 - b|_{\rm BSM} < 10^{-3}$$
$$|b|_{\rm BSM} < 10^{-3}$$

Similar proposal at ORNL by 2015

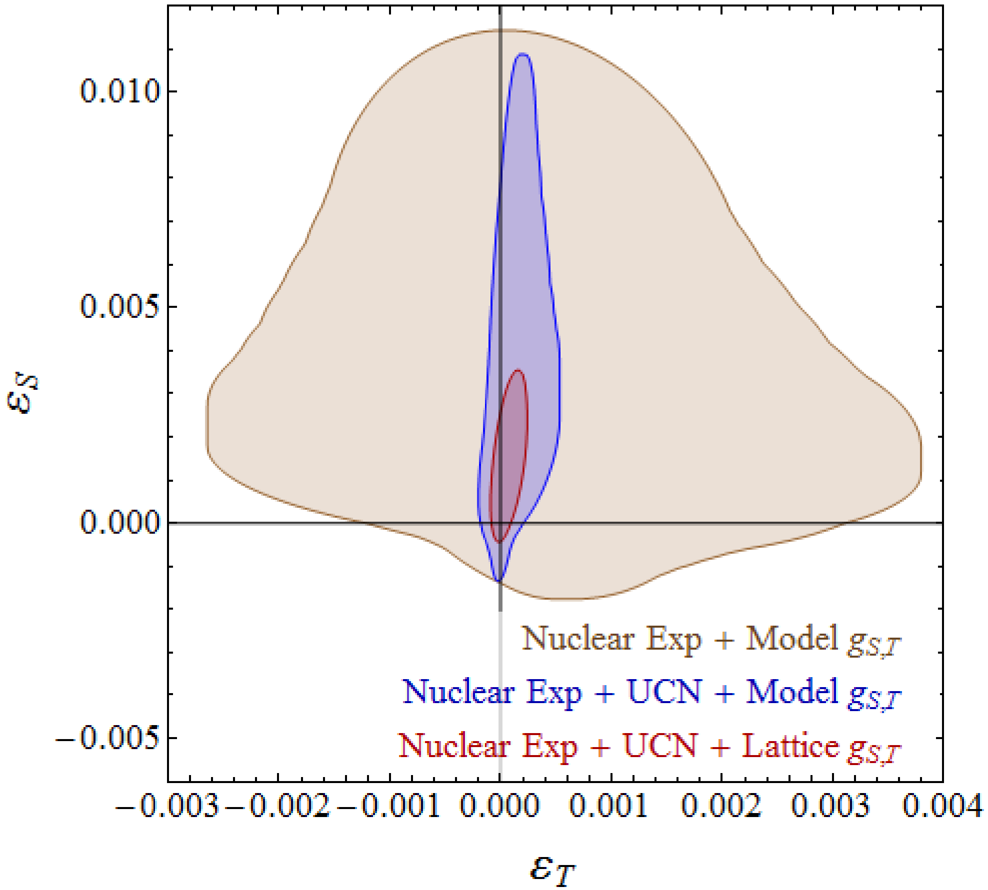
Crucial Role of Theory

§ Given precision $g_{S,T}$ and O_{BSM}, predict new-physics scales

New UCN Exp.

$$O_{\mathrm{BSM}} = f_O(\varepsilon_{S,T}\, g_{S,T})$$

Precision LQCD input
($m_\pi \to 140$ MeV, $a \to 0$)



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Expect by 2013:

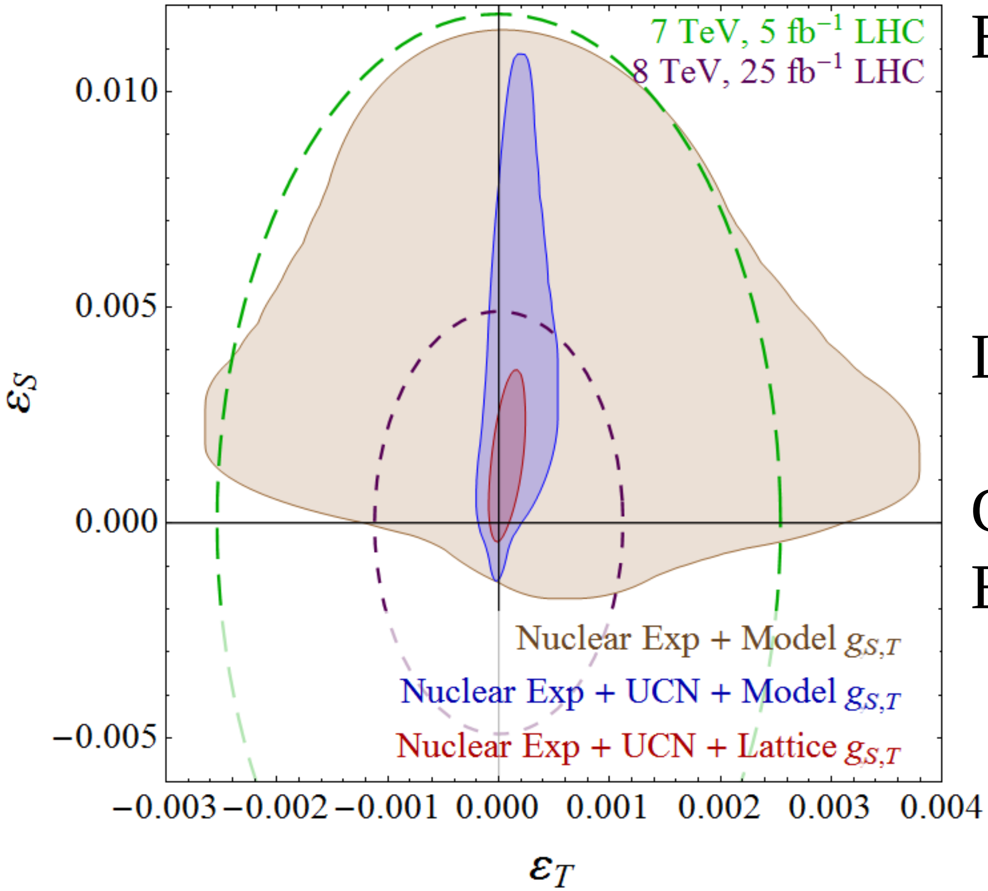
$$|B_1 - b|_{\mathrm{BSM}} < 10^{-3}$$
$$|b|_{\mathrm{BSM}} < 10^{-3}$$

Similar proposal at ORNL by 2015

High-Energy Constraints

§ Constraints from high-energy experiments?

LHC current bounds and near-term expectation



Estimated though effective *L*

$$\mathcal{L} = -\frac{\eta_S}{\Lambda_S^2} V_{ud} (\overline{u}d)(\overline{e}P_L\nu_e) - \frac{\eta_T}{\Lambda_T^2} V_{ud} (\overline{u}\sigma^{\mu\nu}P_L d)(\overline{e}\sigma_{\mu\nu}P_L\nu_e)$$

Looking at high transverse mass in $e\nu + X$ channel

Compare with *W* background

Estimated 90% C.L. constraints on

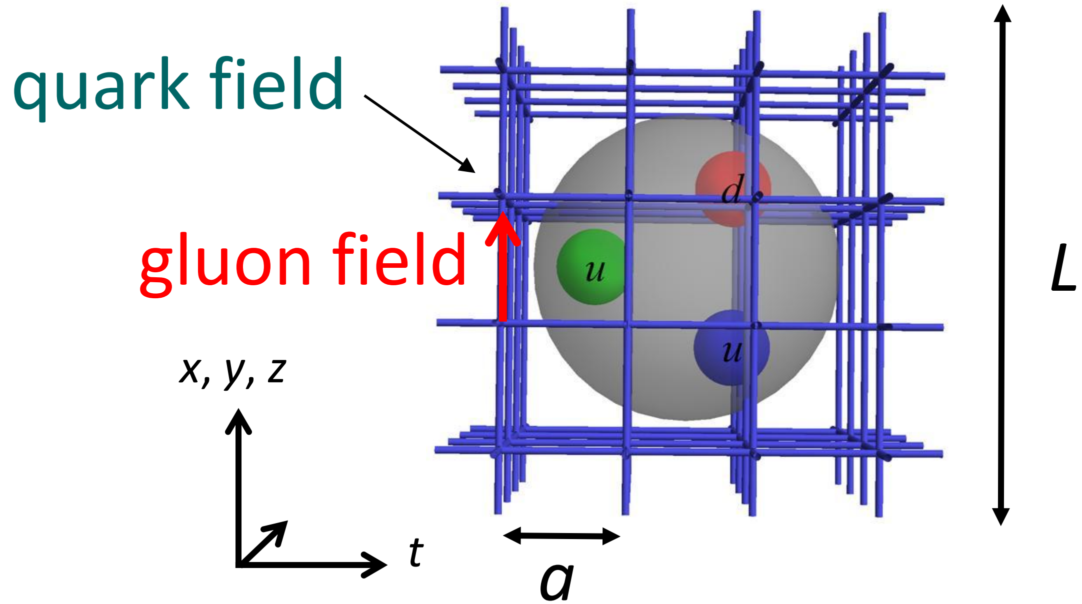
$$\varepsilon_{S,T} \propto \Lambda_{S,T}^{-2}$$

HWL, 1112.2435; 1109.2542

T. Bhattacharya et al, 1110.6448

Lattice QCD Progress

§ Lattice uncertainties:
- Statistical noise
- Unphysical scales a, L
- Extrapolation to M_π



§ Computational costs
- Scaling: $a^{-(5–6)}$, L^5, $M_\pi^{-(2–4)}$

§ Most major 2+1-flavor gauge ensembles: M_π < 200 MeV
- Now including physical pion-mass ensembles

§ Charm dynamics: 2+1+1-flavor gauge ensembles
- MILC (HISQ), ETMC (TMW)

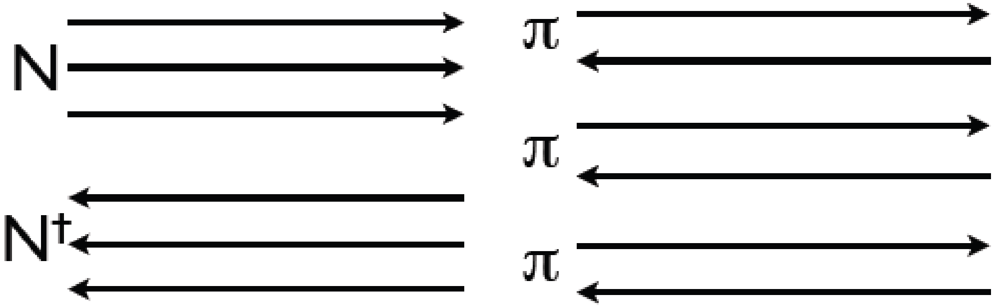
§ Pion-mass extrapolation $M_\pi \to (M_\pi)_{\text{phys}}$

(Bonus products: low-energy constants)

The Trouble with Nucleons

- Difficulties in Euclidean space
- Exponentially worse signal-to-noise ratios
  - Consider a baryon correlator $C = \langle O \rangle = \langle qqq(t)\ \bar{q}\bar{q}\bar{q}(0) \rangle$
  - Variance (noise squared) of $C \propto \langle O^\dagger O \rangle - \langle O \rangle^2$

What you want: What you get:



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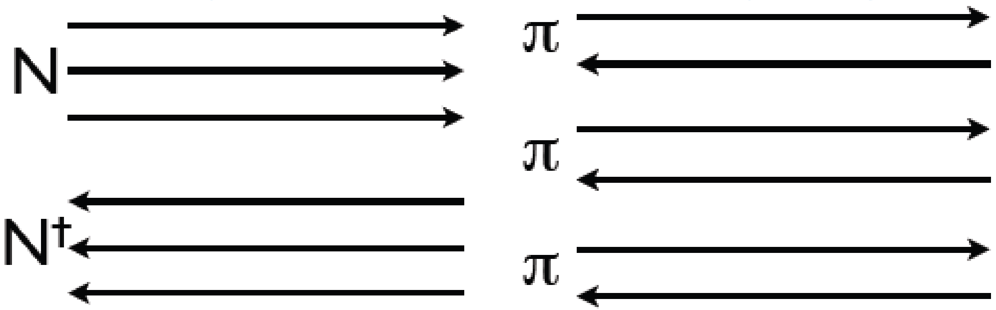
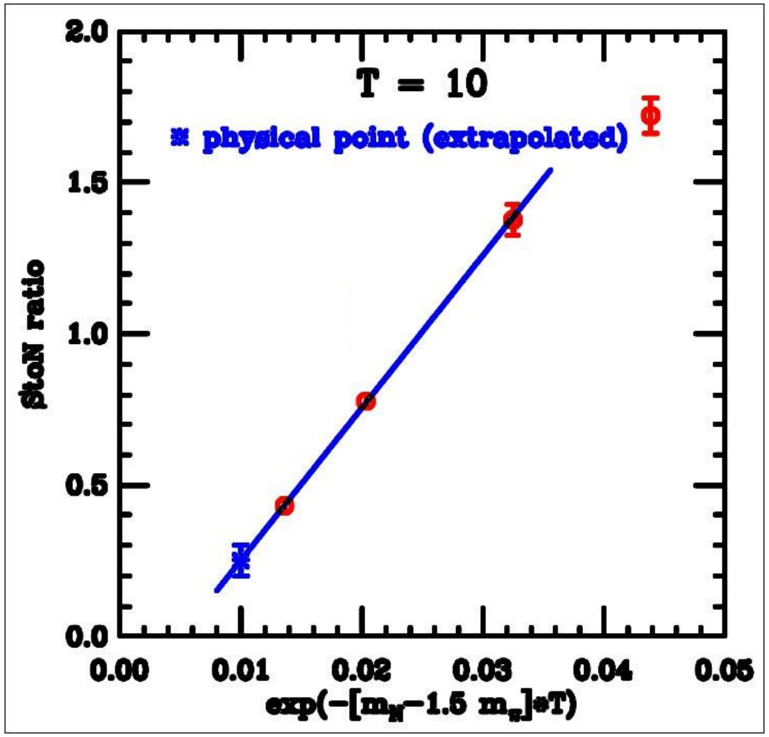


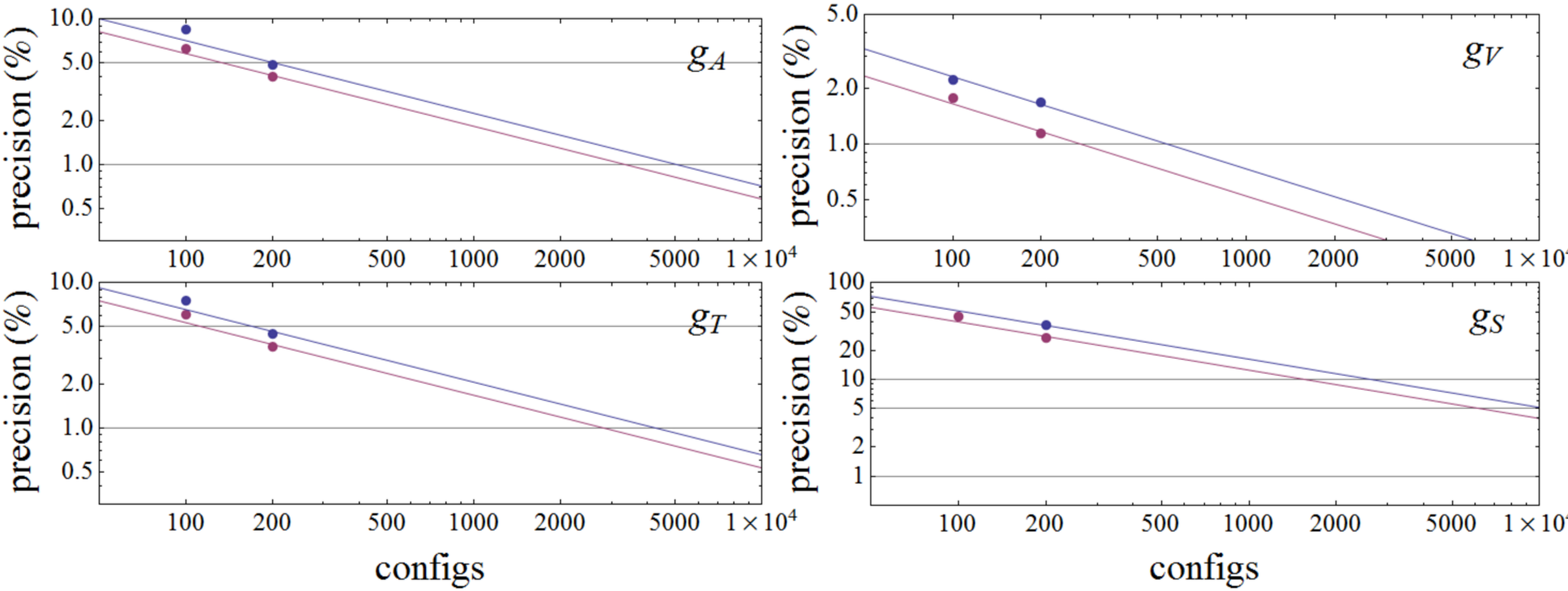


  - Signal falls exponentially as $e^{-m_N t}$
  - Noise falls as $e^{-(3/2) m_\pi t}$
  - Problem worsens with:
    - increasing baryon number
    - decreasing quark (pion) mass

Statistical Uncertainty

§ Targeted statistical on charges: 2% estimation

- Other sources of error: 8% (NPR + continuum extrap. + mixed sys.)
- g_S would be most challenging



Systematic Uncertainties

§ Chiral extrapolation suffers biggest systematic uncertainty

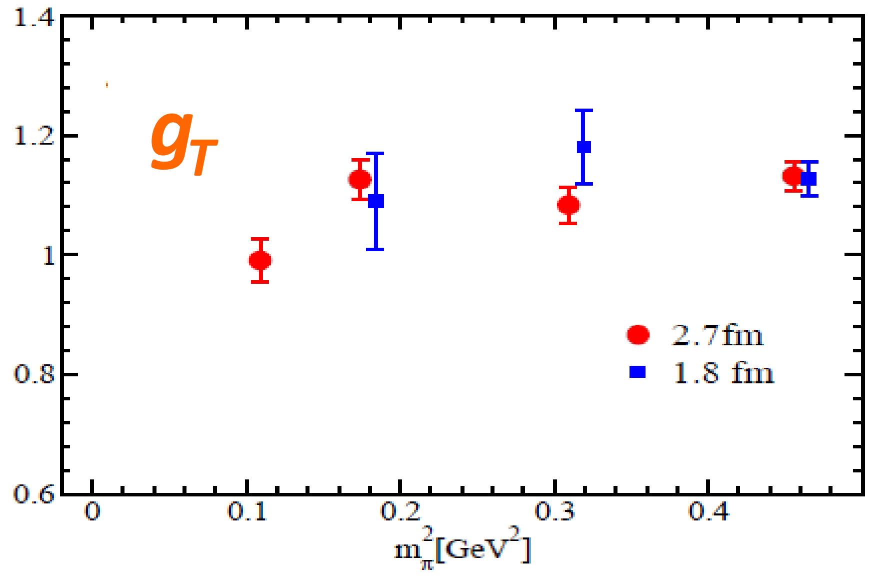
- Huge obstacle to precision measurement
- Issues: validity of XPT over the range of pion masses used, convergence, SU(3) vs. SU(2) flavor, etc.

§ Remaining systematics: finite-volume effects

- Seems pretty well controlled

$m_\pi L \gtrsim 4$

RBC/UKQCD arXiv:1003.3387[hep-lat]



§ Solutions

- Include the physical pion mass in the calculation
- Extrapolate to the continuum limit (use multiple *a*)

PNDME Roadmap

Precision Neutron-Decay Matrix Elements (2010–)

http://www.phys.washington.edu/users/hwlin/pndme/index.xhtml

Tanmoy Bhattacharya

Saul Cohen

Rajan Gupta

Anosh Joseph

HWL (PI)

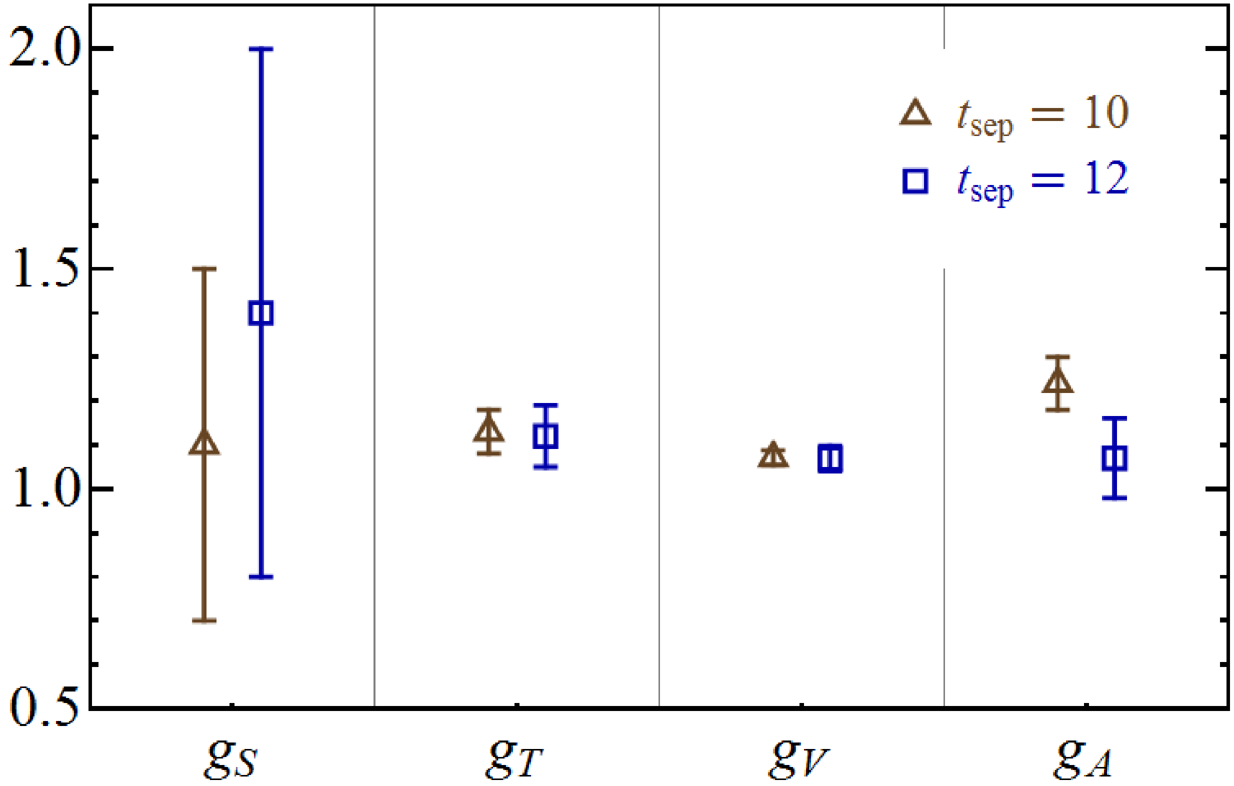
§ Plan

- MILC HISQ (140-MeV π available)
- Jan. 1 – Jun. 30, 2011 (USQCD)
- Apr. 1, 2011 (Teragrid 8M SUs)
- Jul. 1– (USQCD), Dec. (NERSC)
- 10% within 2 years
  O(1%) in 3–4 years

a(fm)	m_l/m_s	Lattice	$m_\pi L$	m_π(MeV)
0.15	1/5	$16^3\times 48$	3.78	306
0.15	1/10	$24^3\times 48$	3.99	217
0.12	1/5	$24^3\times 64$	4.54	309
0.12	1/10	$32^3\times 64$	4.29	221
0.12	1/27	$48^3\times 64$	4.08	140
0.09	1/5	$32^3\times 96$	4.50	314
0.09	1/10	$48^3\times 96$	4.77	222
0.09	1/27	$64^3\times 96$	3.66	129
0.06	1/5	$48^3\times 144$	4.51	315
0.06	1/10	$64^3\times 144$	4.25	227

Excited-State Contamination

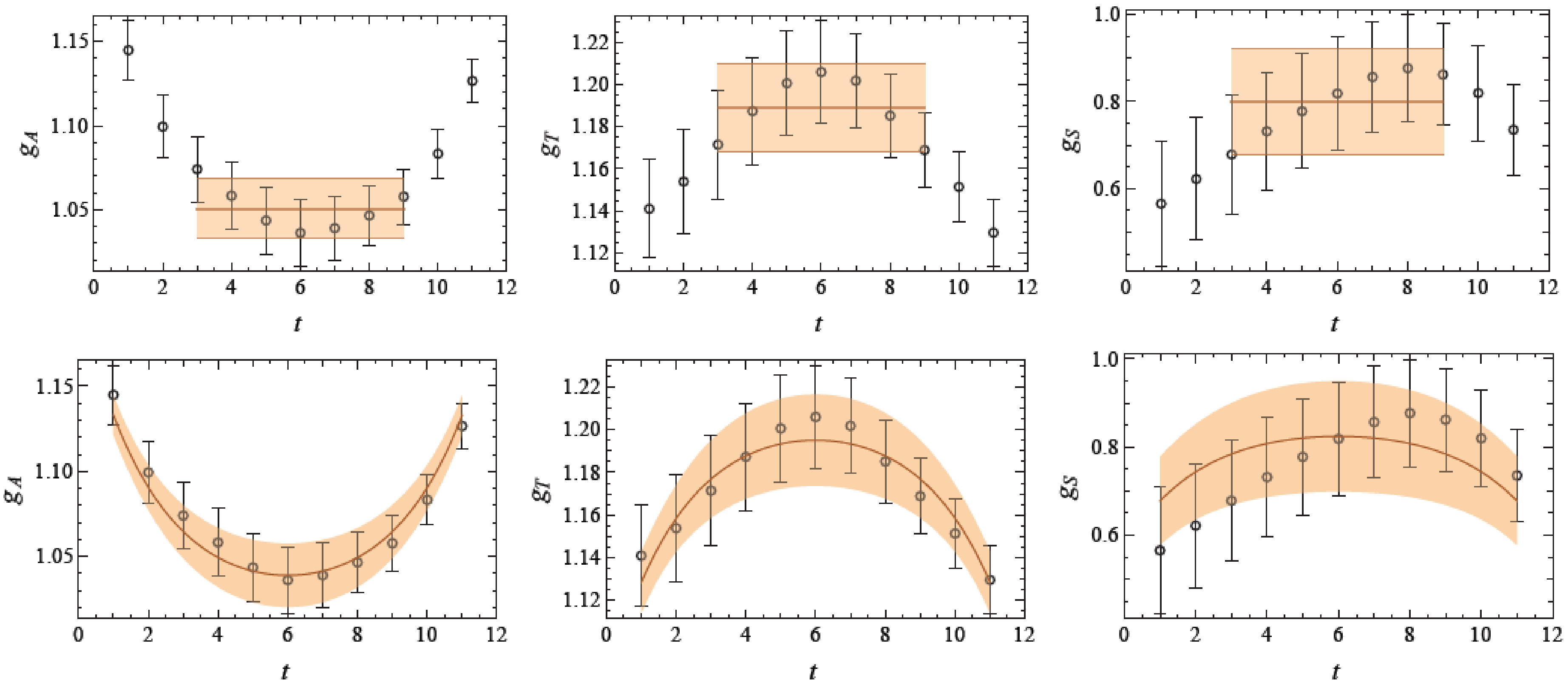
- Explore optimal smearing parameters and multiple source-sink separations



- Analyze the three-point function including excited state

Excited-State Contamination

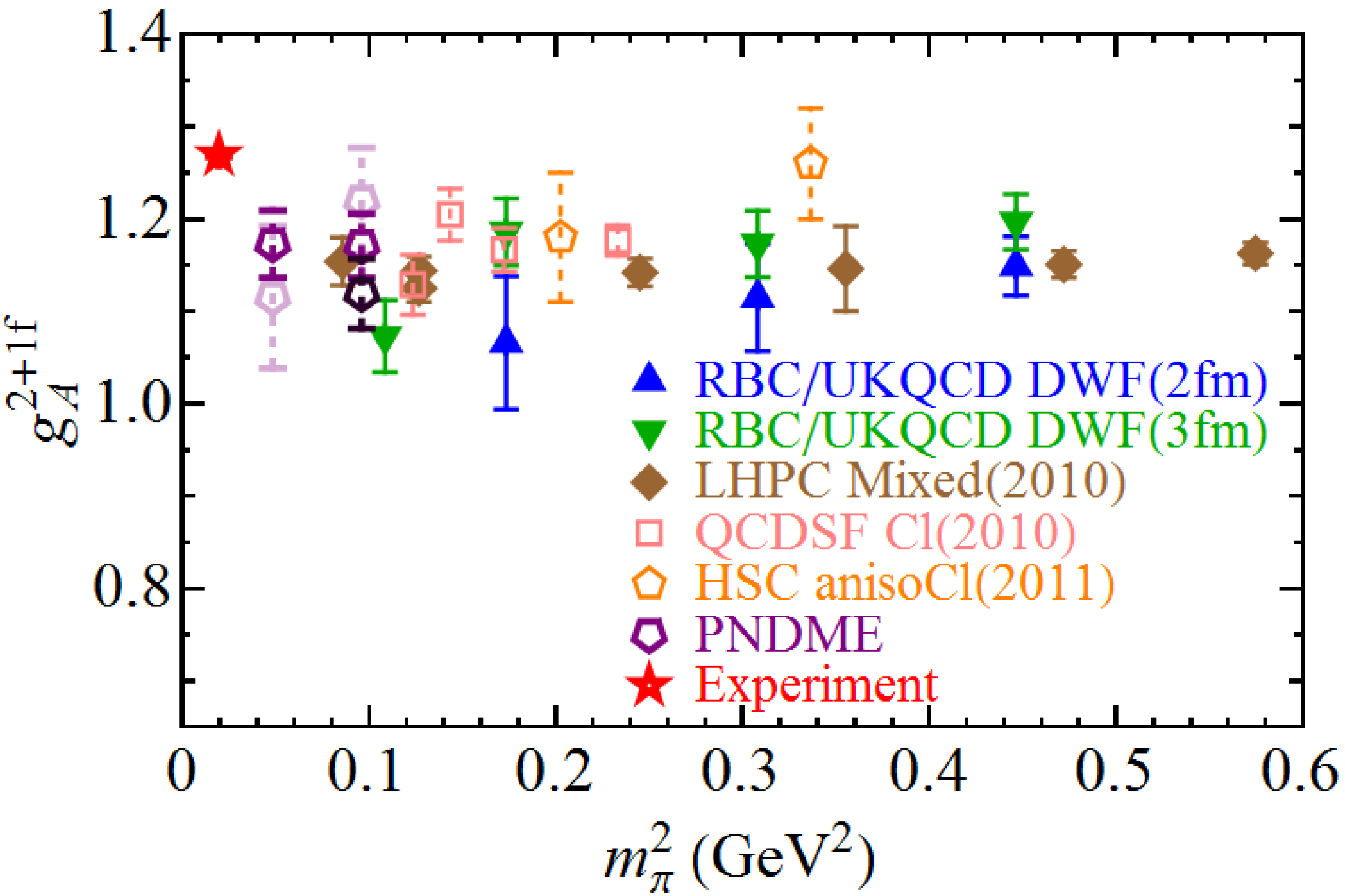
- Explore optimal smearing parameters and multiple source-sink separations (0.96—1.44fm)
- Analyze the three-point function including excited state



Isovector Axial Charge

§ Our preliminary numbers and world $N_f = 2+1$ values

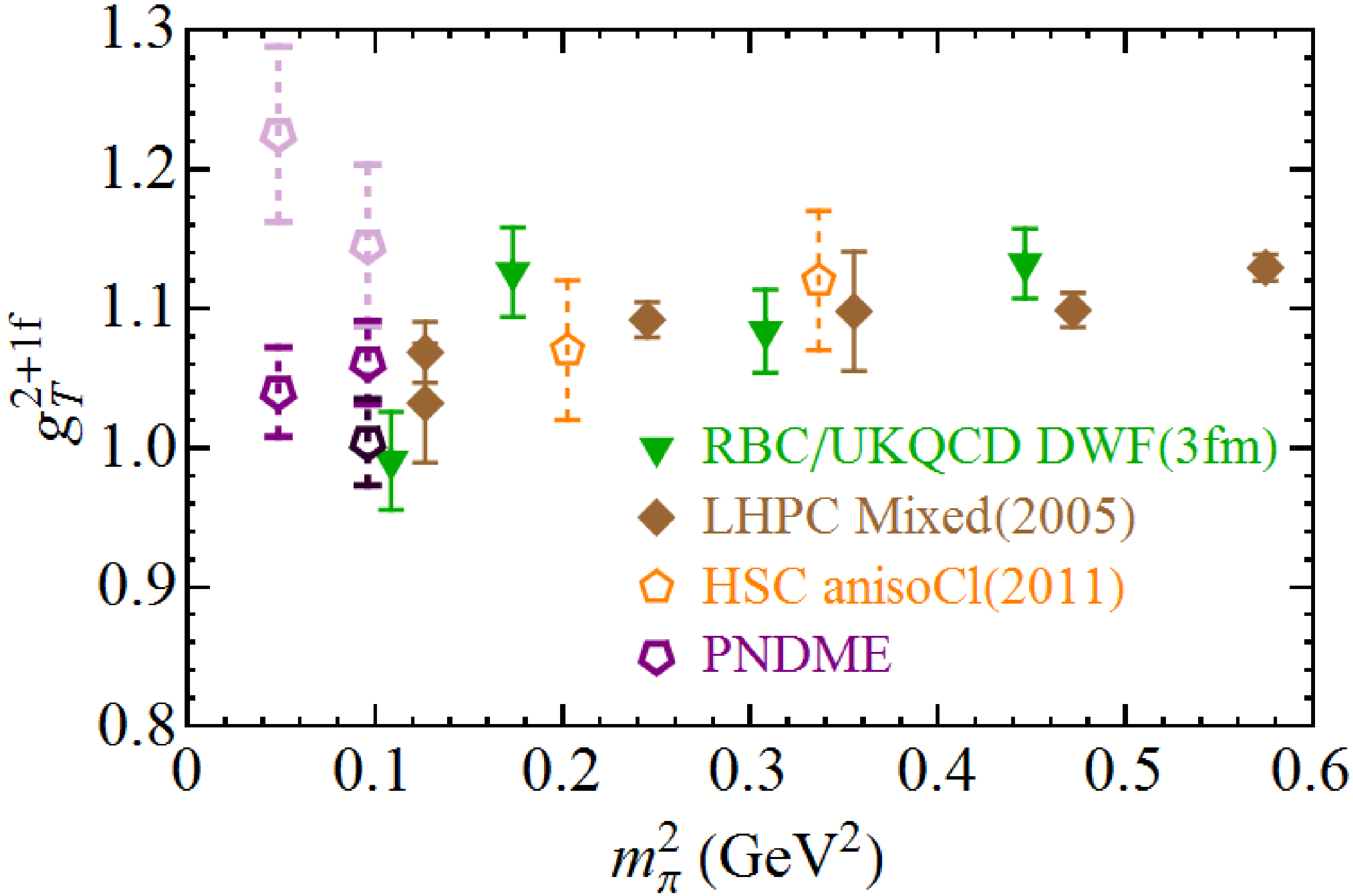
- a = **0.06**, **0.09**, **0.12** fm, 220- and 310-MeV pion



Isovector Tensor Charge

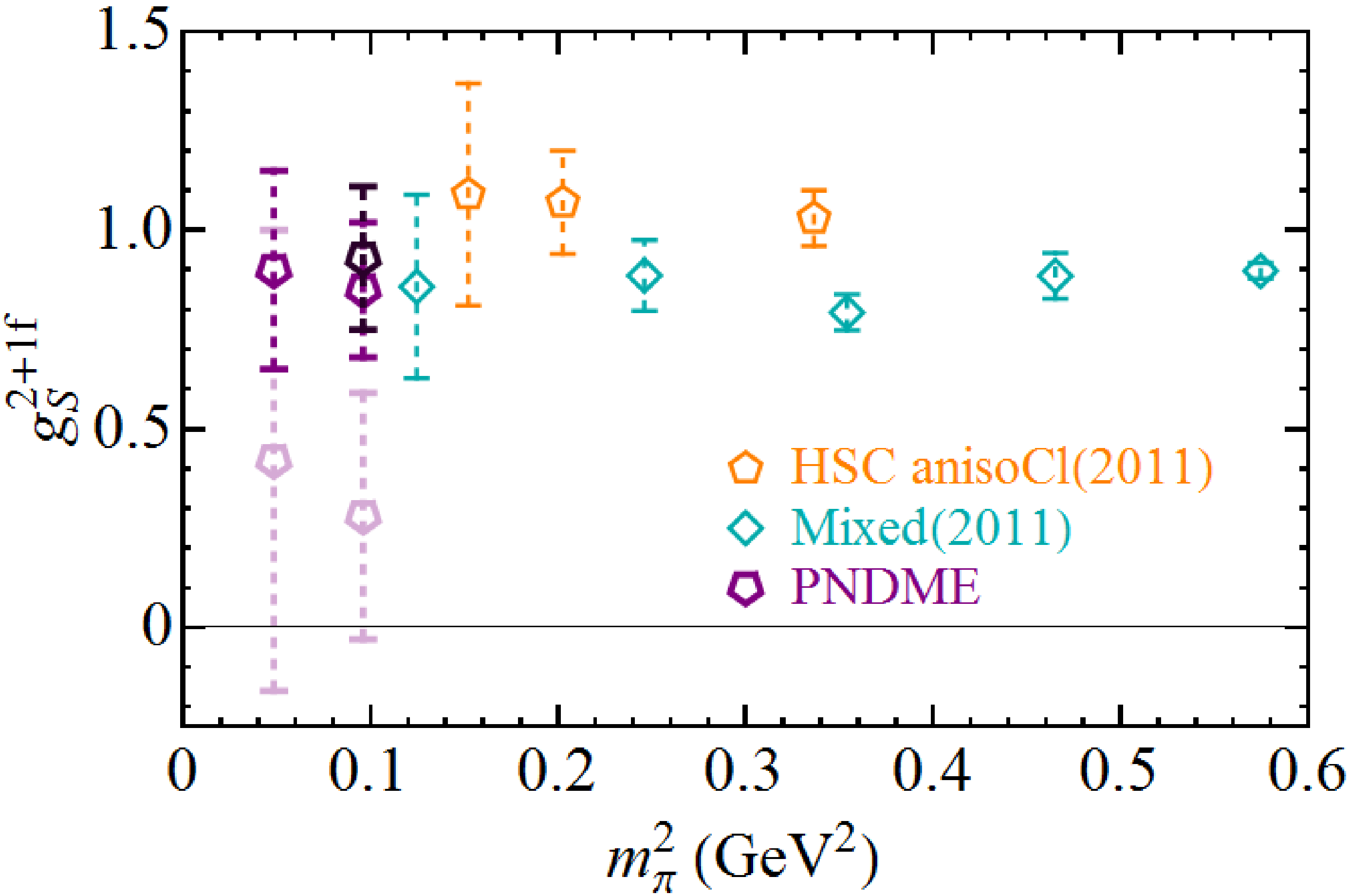
§ Our numbers (unrenormalized) and other $N_f=2+1$ values

- a = **0.06**, **0.09**, **0.12** fm, 220- and 310-MeV pion



Isovector Scalar Charge

- Our numbers (unrenormalized) and other $N_f = 2+1$ values
- g_S becomes much noisier at light pion mass



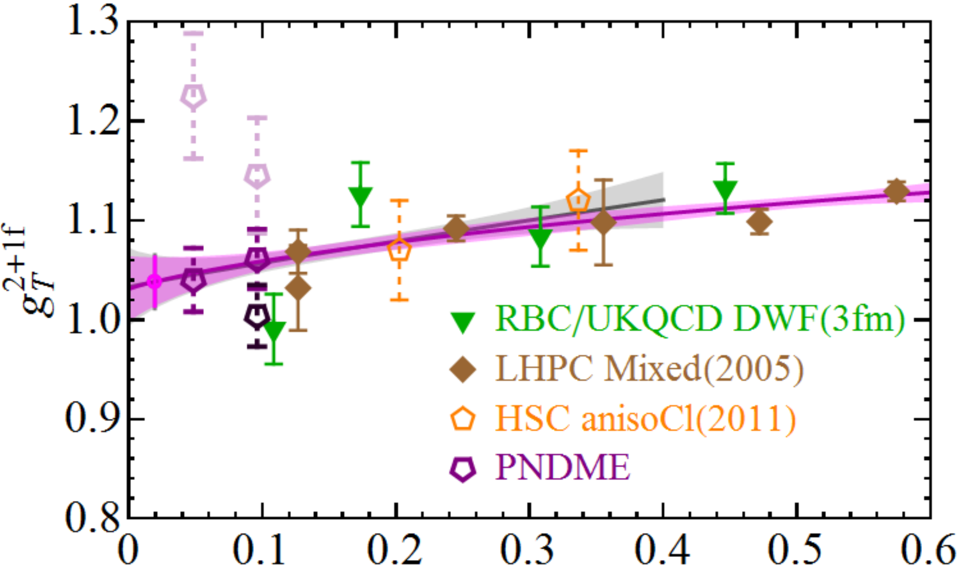
Preliminary Results

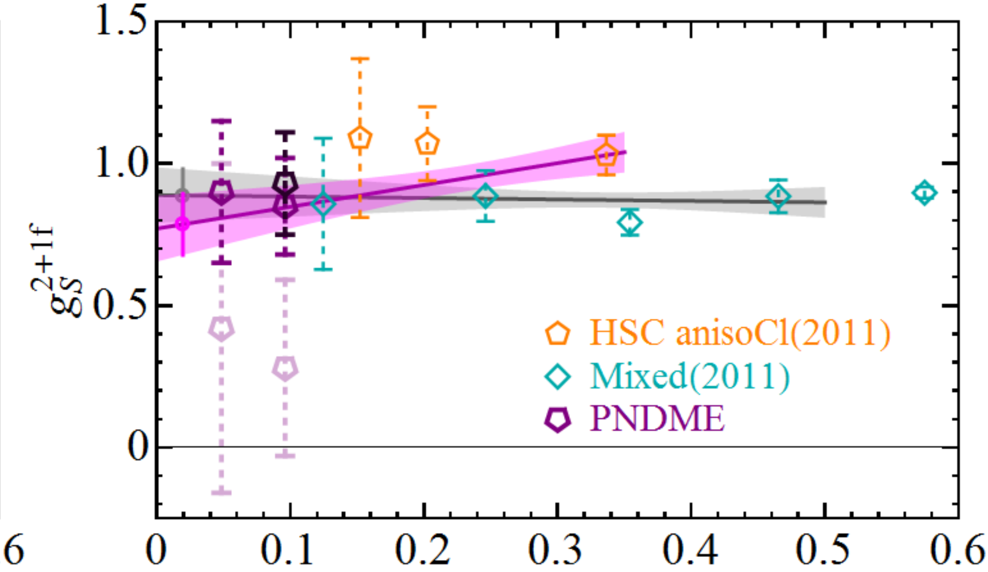
§ Tensor charge: the zeroth moment of transversity

- Probed through SIDIS: $g_T(Q^2{=}0.8\ \text{GeV}^2) = 0.77^{+0.18}_{-0.24}$
- Model estimate 0.8(4)

§ Scalar charge $\langle n|\bar{u}d|p\rangle$

Prior model estimate: $1 \gtrsim g_S \gtrsim 0.25$





$g_T^{\text{LQCD}} = 1.05(4)$ $\quad m_\pi^2\ (\text{GeV}^2)$ $\quad g_S^{\text{LQCD}} = 0.79(9)$

HWL, 1112.2435; 1109.2542

The name of the game is precision

- The precision frontier enables us to probe BSM physics
  - Opportunities combining both high- (TeV) and low- (GeV) energy
- Exciting era using LQCD for precision inputs from SM
  - Increasing computational resources and improved algorithms
  - Enables exploration of formerly impossible calculations
- Necessary when experiment is limited
- Bringing all systematics under control